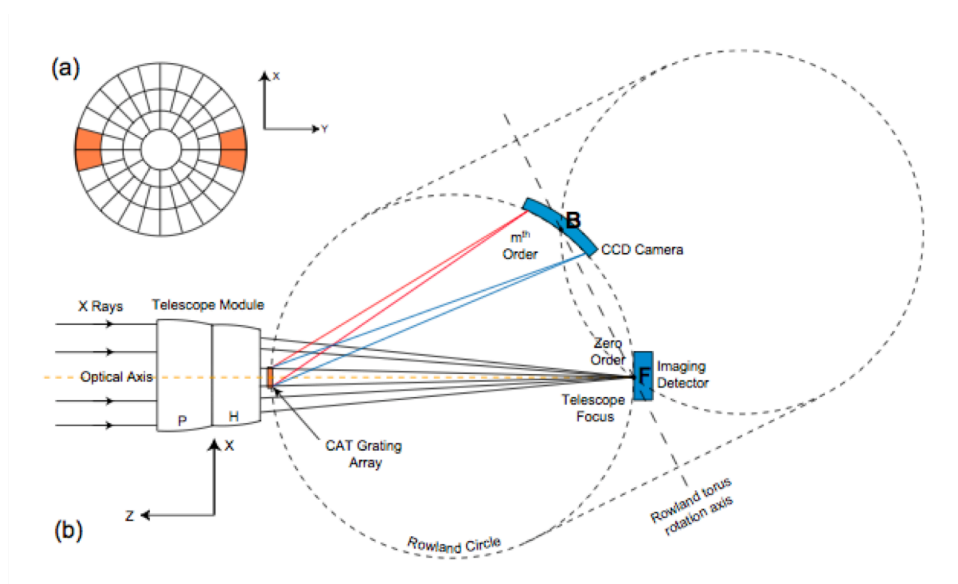




## Critical Angle Transmission X-ray Grating Spectrometer Technology Development Plan



Prepared by  
The IXO CAT XGS Team

# Critical Angle Transmission X-ray Grating Spectrometer Technology Development Plan

## Introduction

### CAT XGS Description

The IXO X-ray Grating Spectrometer (XGS) is a wavelength-dispersive high-resolution spectrometer offering spectral resolution  $\lambda/\Delta\lambda = 3000$  (FWHM) and effective area of 1000 cm<sup>2</sup> in the 0.3-1 keV spectral band. The reference concept incorporates arrays of gratings that intercept a portion of the converging beam from the flight mirror assembly and disperse the X-rays onto a CCD detector array.

The Critical Angle Transmission (CAT) XGS is one of two candidate approaches to the IXO XGS instrument. The CAT XGS relies on a novel optical element recently developed at MIT: the critical angle transmission (CAT) grating. The CAT grating is a blazed X-ray transmission grating that provides high-dispersion spectroscopy with excellent efficiency over a broad spectral band with low mass and relatively relaxed alignment tolerances (Heilmann et al., 2008). The most recent account of the CAT XGS optical principles, state of development and configuration is given by Heilmann et al (2009).

The IXO CAT XGS is shown schematically in Figure 1. Arrays of CAT gratings are located behind four of the 24 outer ring modules of the flight mirror assembly. The gratings are mounted tangent to the Rowland torus. They diffract X-rays through a range of angles near the grating blaze angle ( $\sim 1.5$  degrees) and the dispersed spectrum is recorded by a dedicated CCD camera at B, displaced from the mirror focus F. Thus the complete CAT XGS instrument consists of a set of grating arrays and a readout subsystem. The CAT grating has high diffraction efficiency in many (up to 10) orders near the blaze angle, and the intrinsic energy resolution of the CCD detectors is used to separate the overlapping orders.

The CAT grating array mounting concept is shown in more detail in Figure 2. Each grating array contains 44 individual grating membranes, and each membrane is secured within a facet frame. The individual CAT grating membranes,  $\sim 6 \times 6$  cm in size, are produced from conventional silicon-on-insulator (SOI) wafers using nanofabrication techniques. The grating bars within a membrane are fabricated in the 6  $\mu\text{m}$ -thick SOI device layer, and are nominally 40 nm wide and 6  $\mu\text{m}$  deep; the grating bar period is 200nm. The grating bars are supported by a two-level structure fabricated in the silicon wafer along with the grating bars. The finer "Level-1" supports are fabricated in the SOI device layer; the coarser "Level 2" supports are fabricated in the  $\sim 500 \mu\text{m}$ -thick SOI handle layer.

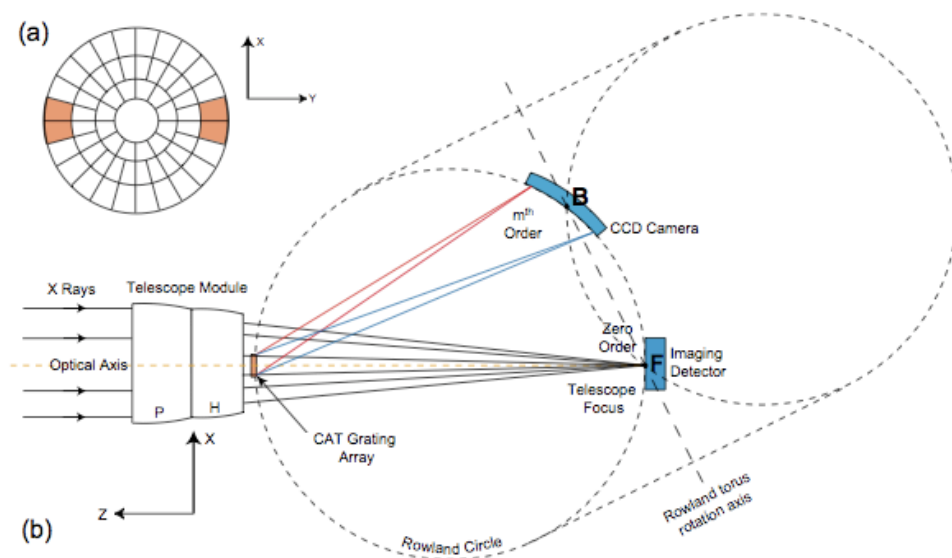


Figure 1: Schematic of the CAT XGS. a) View of the flight mirror assembly from the telescope focus. Four outer ring modules (shaded) are covered by the gratings. b) Schematic of optical design (not to scale). X-rays are focused by the telescope module onto the focus F. CAT gratings intercept a fraction of the X-rays and diffract them predominantly at angles centered around the blaze direction. Representative paths for longer (red) band shorter (blue) wavelength rays diffracted in one order are shown. The CAT grating has high diffraction efficiency in many orders.

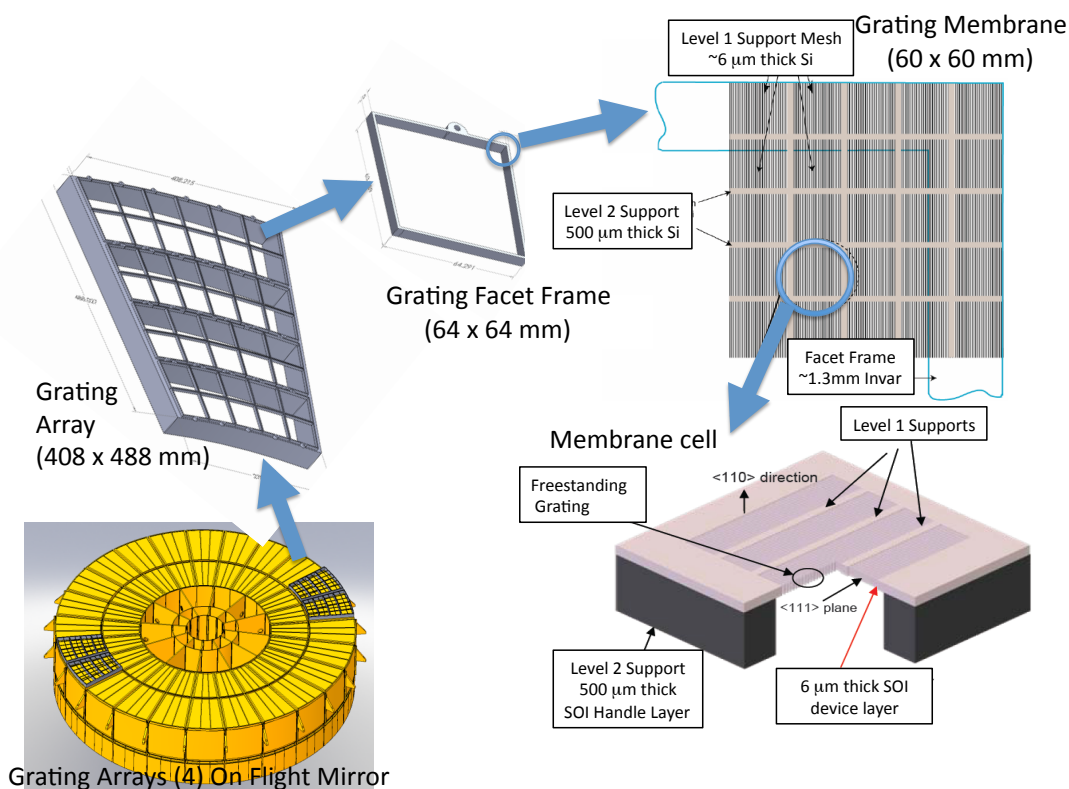


Figure 2: CAT grating array and mounting concept and grating membrane structure.

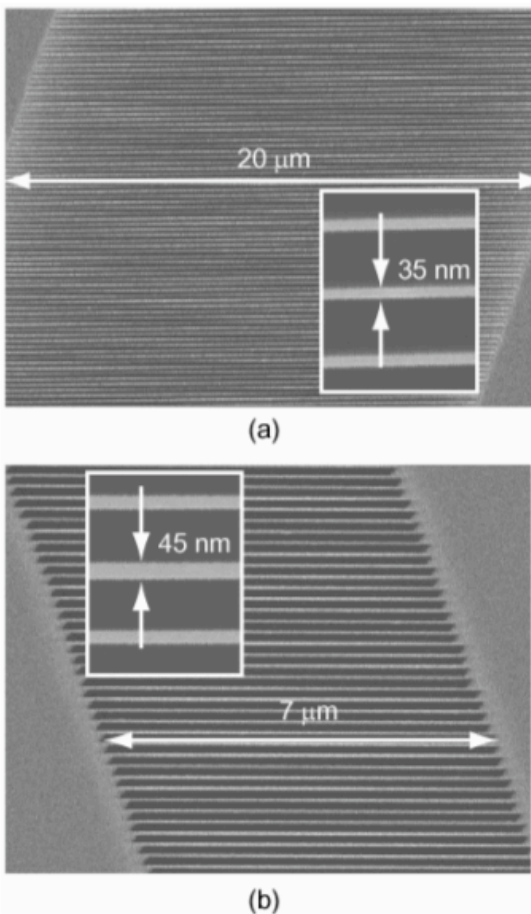
### CAT XGS Heritage

X-ray transmission gratings have a long flight history dating to the Einstein Observatory, which operated in the 1970s. The CAT XGS is a direct descendant of the high-energy transmission grating (HETG) spectrometer, launched in 1999 and still operating successfully on the Chandra X-ray Observatory. The MIT group that built the HETG grating array for Chandra will lead the fabrication of the CAT XGS grating membranes and grating array.

X-ray CCD detectors also have a rich flight heritage, having flown on at least six high-energy astrophysics missions since their first use on the ASCA satellite, launched in 1993. The CAT XGS CCDs are very similar to those currently in use on the *Suzaku* mission and descend directly from those now operating on Chandra.

## Technology Development Plan

### Current Technology Status



**Figure 3: Scanning electron micrographs of recently fabricated CAT test gratings. The grating bars have the required period (200nm), depth (6 microns) and width (35-40 nm). The Level-1 support bars are trapezoidal, with a spacing of 20 microns at the top (a) but only 7 microns at the bottom (b).**

Technology development is required for the CAT grating arrays and for the readout subsystem. Test gratings with the required period (200nm), bar-thickness (40nm) and bar aspect ratio (150:1) have been successfully tested, and show 80%-100% of the theoretically expected diffraction efficiency. Scanning electron micrographs of test articles are shown in Figure 3. These test articles have a grating area of 3 x 3 mm<sup>2</sup> and an open area fraction of approximately 45%. The CAT grating element is currently at TRL 3.

The CAT XGS CCD detectors are modified versions of devices currently operating on *Chandra* and *Suzaku*. These devices have the X-ray detection efficiency and spectral resolution required for the CAT XGS. Like all X-ray CCDs, they require optical blocking filters (OBF) to reject out-of-band “optical” (i.e., ultraviolet, visible and near-infrared) radiation which would otherwise degrade detector performance. These filters inevitably absorb X-ray photons as well, reducing system throughput. Sensitivity

to optical light can be minimized in X-ray photon-counting systems by reducing the CCD integration period, since this minimizes the number of incident optical photons per readout for a given optical flux. For the CAT XGS we will increase the CCD readout speed, reduce the minimum integration time, and thus reduce the required OBF thickness. To further minimize OBF thickness, we will deposit the filters directly on the CCDs. For application to CAT XGS, current detectors are at TRL 5. We have therefore planned modest technology development efforts for the CAT XGS readout system.

### Technology Development Tasks

The remaining challenges for CAT XGS technology development are 1) to modify grating fabrication techniques to produce Level-1 and Level 2 support structures with larger open areas (approaching 90%) while achieving larger grating area; 2) to adapt alignment techniques originally developed for the Chandra ACIS HETG spectrometer for use in aligning CAT XGS grating membranes within an array and 3) to enhance the CCD detectors and readout subsystem to maximize low-energy detection efficiency. We will achieve these goals by performing six technology development tasks. These are discussed in the following two sections. The schedule for performing these tasks follows as Figure 4.

### Grating Fabrication Technology Development

*Task 1: Develop fabrication method for high-throughput Level 1 supports.* As shown above in Figure 2, the CAT grating bars are supported by a two-level structure fabricated in the same SOI wafer in which the gratings are formed. The fine supports (Level 1) are fabricated in the SOI device layer. The area obscured by these supports must be increased to achieve the desired grating throughput.

The Level 1 supports are currently etched at the same time as the CAT grating bars. A chrome mask defines the Level 1 supports, while a silicon nitride mask, generated by scanning-beam interference lithography (Heilmann et al. 2004), defines the grating bars. The device-layer etch in KOH solution relies on the etch anisotropy between {111} and {110} planes of silicon in the <110> SOI wafers, and is highly dependent on the precise alignment of between the nitride grating bar pattern and the silicon crystal planes.

A disadvantage of the current device-layer etch scheme is that the KOH etch stops not only on the grating bar walls, but also on other, 'non-vertical' {111} planes. This leads to significant broadening of the Level-1 supports with increasing depth, and concomitant narrowing of the slots between the grating bars (compare Figure 3a and 3b). In this task we will develop other anisotropic etch processes that are insensitive to silicon crystal orientation and we will apply them to the fabrication of Level 1 supports the required throughput.

*Task 2: Develop high-throughput Level 2 supports.* The Level-2 support structure is fabricated in the handle-wafer side of the SOI wafer. For the 3 x 3 mm<sup>2</sup> test gratings fabricated to date, this etch defines a single frame. For the 60 x 60 mm<sup>2</sup> CAT XGS grating, the Level-2 support will be a coarse grid structure. In this task we will

demonstrate fabrication of a suitable support grid with adequate open fraction over the desired grating area. Diffraction efficiency and open area will be verified with X-ray testing of full-sized gratings.

*Task 3: Detailed facet/frame design, membrane integration and alignment process development.* Each full-size grating membrane must be integrated with a facet frame so that it can be mounted in the grating array structure. The various grating facets must then be aligned with one another. In this task we will draw on our experience in assembling and aligning grating facets for Chandra HETG to develop the procedures required for the IXO CAT XGS.

This task will include fabrication, alignment and X-ray and environmental testing of a brassboard grating array structure (see Figure 2) partially populated with full-sized grating facets. We anticipate reaching TRL 5 (X-ray performance verification) for the grating array by October 2012, and TRL 6 (full environmental testing complete) by September, 2013.

#### Readout Subsystem Technology Development

*Task 4: Modify CCD for faster readout.* The baseline CCD detector for the CAT XGS, the MIT Lincoln Laboratory CCID41, is a 1024x1024 pixel frame transfer device with four output nodes. Front- and back-illuminated versions of these detectors are successfully operating on the *Suzaku* mission; the CAT XGS will use back-illuminated devices. The CCID41 is a direct descendant of the CCID17, currently operating in Chandra's ACIS instrument. The primary difference between the CCID41 and CCID17 is the presence of a charge injection register on the former. This feature has proven effective in mitigating the effects of radiation exposure and will be retained for the CAT XGS.

On the *Chandra* and *Suzaku* missions, the readout speed of the devices is slower (100 kHz and 42 kHz per node respectively) than required for CAT-XGS, which is to operate at 500 kHz per node. With the expected on-chip binning, this will result in a frame readout rate in excess of 14 frames/s. Two detector design modifications are planned to minimize power consumption and maintain noise performance at this higher speed. This task will entail the necessary design work, fabrication of one lot of test detectors, and follow-up testing to verify performance requirements are met.

The planned detector design modifications are:

1. Addition of metal 'straps' to the parallel transfer gate busses and electrodes to minimize gate impedance, voltage drop and power consumption during readout. This change has been successfully implemented on other Lincoln Laboratory devices. Since the CAT XGS detectors are back-illuminated, the additional strapping will not affect detection efficiency.
2. Replacement of the existing, on-chip MOSFET output source-follower with a higher responsivity JFET device to maintain low noise performance at the higher readout speed. The JFET amplifier has already been demonstrated in

the laboratory on a small test detector. A factor of two increase in responsivity is expected.

*Task 5: Develop directly-deposited thin-film optical blocking filters.* As noted above, thin film “optical” blocking filters (OBF) are required to avoid CCD performance degradation in the presence of stray light in the UV, visible and near-IR. The X-ray opacity of the OBF must be minimized to achieve the required system detection efficiency in the CAT XGS band ( $0.3 \text{ keV} < E < 1 \text{ keV}$ ). Moreover, the higher readout rate of CAT XGS CCDs (discussed in Task 4 above) will reduce the required optical opacity, and should make it possible to employ thinner OBFs than have been used on previous missions. Finally, the relatively large area ( $\sim 200 \text{ cm}^2$ ) of CAT XGS focal plane renders free-standing filters problematic. For these reasons, directly deposited OBFs are planned for the CAT XGS.

Directly deposited blocking filters have been used successfully on previous missions (notably the XMM/Newton RGS), and we have laboratory experience with relatively thick (aluminum+parlylene  $\sim 200\text{nm}$  total thickness) directly deposited OBFs. However, we have not yet demonstrated directly deposited filter as thin as those contemplated for CAT XGS ( $< 50\text{nm}$ ) with the back-illuminated CAT XGS devices.

In this task we will define CAT XGS OBF requirements in detail and use devices fabricated in support of Task 4 to develop directly-deposited filters that meet CAT XGS requirements. We will test these filters for transmission and uniformity in the UV, visible and near-IR and X-ray bands

*Task 6: Develop low-power, radiation-tolerant readout electronics.* The basic electronic architecture for the CCD control and readout electronics has been developed for a number of previous missions and is well-understood. Given the relatively large number of parallel output channels (128) and the higher readout rates, it is desirable to reduce power and mass requirements for the readout electronics by integrating components where possible. In particular, it has been demonstrated by members of the CAT XGS team that elements of the analog signal chain can be integrated with the analog-to-digital conversion function in application-specific integrated circuits (ASIC)(Nakajima et al., 2009). This implementation requires further development to demonstrate adequate noise performance at CAT XGS readout rates, and to achieve the necessary radiation tolerance ( $> 54 \text{ krad Si}$  for a 10-year mission).

In this task we will build on existing ASIC designs to develop a CCD readout ASIC that meets CAT XGS requirements for noise performance and radiation tolerance. We expect that three iterations of the design/fabricate/test cycle will be required. The performance of the final ASIC design will be measured with devices from the detector development lot described in Task 4, and radiation tolerance will be demonstrated.

## Technology Development Schedule

The schedule for the six CAT XGS technology development tasks is shown in Figure 4. Tasks 1-3 promote the gratings to TRL 5 by October, 2012. Grating TRL 6 is achieved with the demonstration of the brassboard grating array by September, 2013. TRL 6 for the CCDs and readout ASIC are achieved by September, 2012.

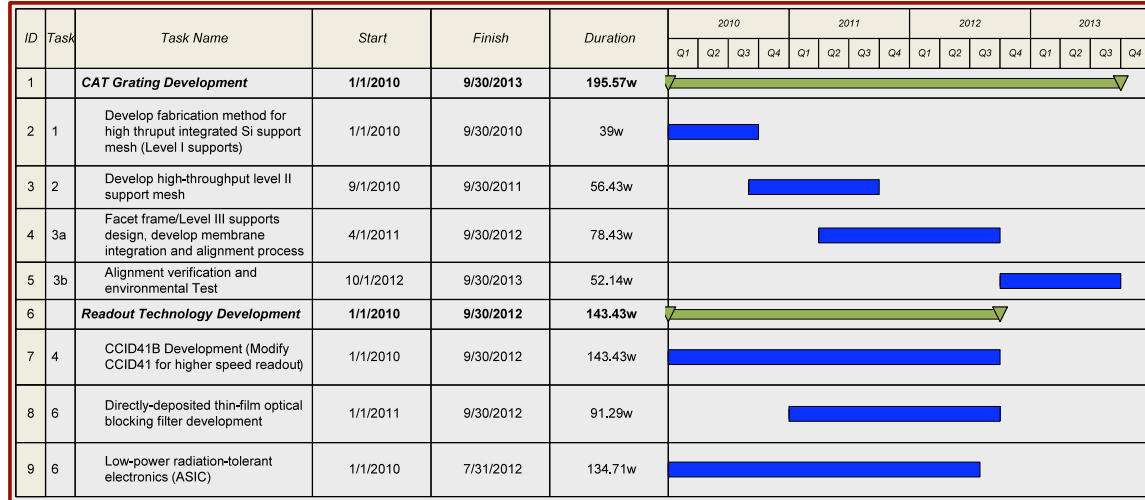


Figure 4: CAT XGS technology development schedule

## References

Heilmann, R. K., Ahn, M., Gullikson, E. M. and Schattenburg, M. L. "Blazed high-efficiency x-ray diffraction via transmission through arrays of nanometer-scale mirrors." *Optics Express* 16 (2008): 8658.

Heilmann, R. K., Chen, C. G., Konkola, P. T. and Schattenburg, M. L. "Dimensional metrology for nanometer-scale science and engineering: Towards sub-nanometer accurate encoders." *Nanotechnology* 15 (2004): S504-S511.

Heilmann, R.K., Ahn, M., Bautz, M. W., Foster, R., Huenemoerder, D., Marshall, H., Mukherjee, P., Schattenburg, M., Schulz, N. and Smith, M. "Development of a critical angle transmission grating for the International X-ray Observatory." *SPIE* 7437 (2009).

Nakajima, H., Matsuura, D., Anabuki, N., Miyata, E., Tsunemi, H., Doty, J., Ikeda, H., Takashima, T. and Katayama, H. "Performance of an Analog ASIC Developed for X-ray CCD Camera Readout System Onboard Astronomical Satellite." *IEEE Transactions on Nuclear Science* 56 (2009): 747-751.